

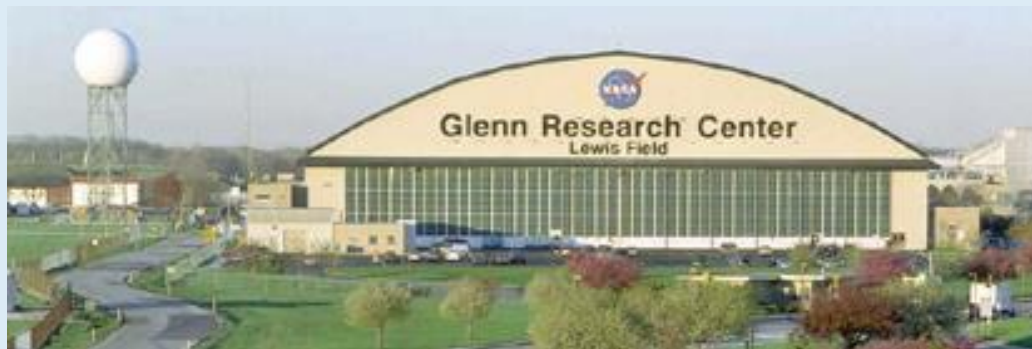


# Overview of CMC (Ceramic Matrix Composite) Research at the NASA Glenn Research Center

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- **John H. Glenn Research Center (GRC) at Lewis Field is one of nine National Aeronautics and Space Administration (NASA) Centers**
- **Originally: NACA (National Advisory Committee on Aeronautics) Engine Research Laboratory (Refr. 1)**



# NASA Glenn Core Competencies



**Air-Breathing Propulsion**



**In-Space Propulsion and  
Cryogenic Fluids Management**



**Physical Sciences and  
Biomedical Technologies in Space**



**Communications Technology  
and Development**



**Power, Energy Storage and  
Conversion**



**Materials and Structures  
for Extreme Environments**



## **Overview**

- **SiC/SiC CMCs and EBCs (environmental barrier coatings)**
- **Background information / Applications**
- **Current and Future NASA GRC CMC/EBC Research**

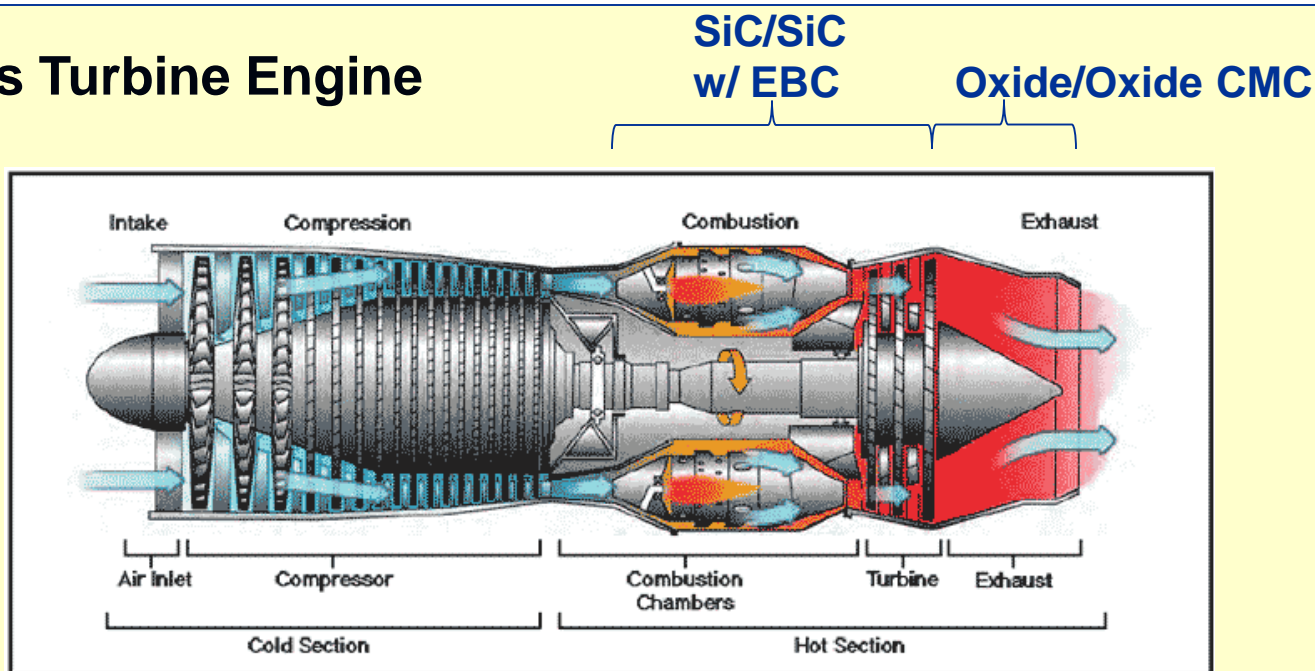
## **Acknowledgment**

**The GRC CMC R&D described in this presentation was performed or is being performed primarily by Materials and Structures researchers and technologists**

# SiC/SiC CMCs: Applications and Need for Coatings

- **SiC/SiC (SiC fiber reinforced SiC matrix) CMCs** are being developed for / utilized in aircraft gas turbine engine hot section component applications ( $T \geq 2200^{\circ}\text{F}$  ( $1204^{\circ}\text{C}$ )) (Refr. 2, 3).
- These CMC components will have an **environmental barrier coating (EBC)**, which is a protective, multilayer oxide surface coating to prevent environmental degradation.

## Aircraft Gas Turbine Engine





# **SiC/SiC Components for Gas Turbine Engines: Benefits**

- **Reduced component weight (1/3 density of superalloys)**
- **Higher temperature capability/increased thermal margin**
- **Reduced cooling requirements**
- **Improved fuel efficiency**
- **Reduced emissions (NO<sub>x</sub> and CO)**

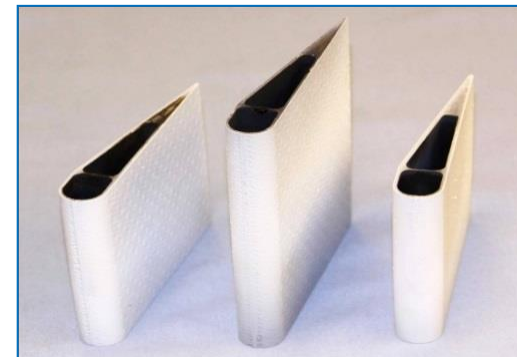
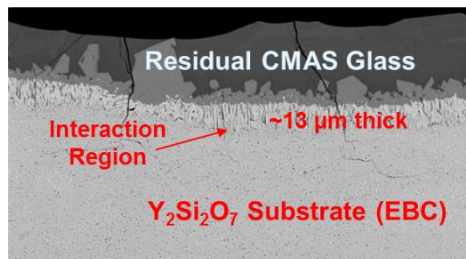
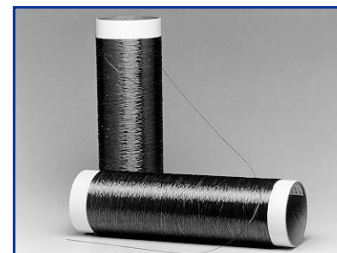
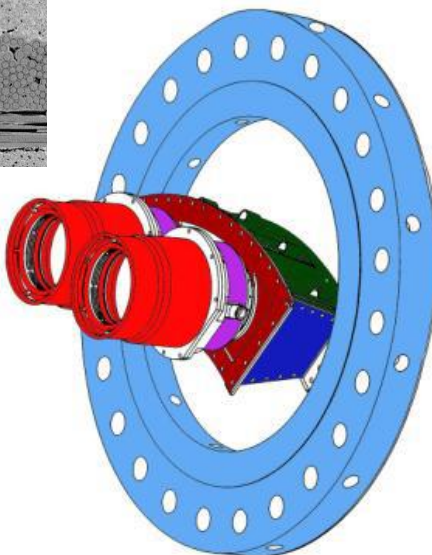
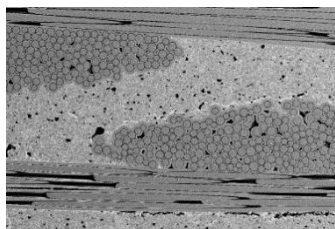
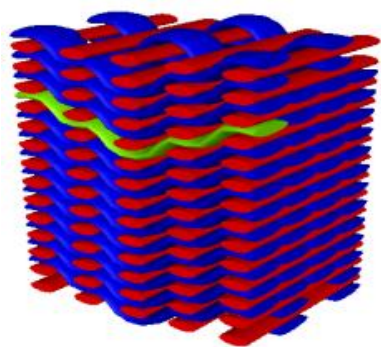


**Refr. 2, 4**



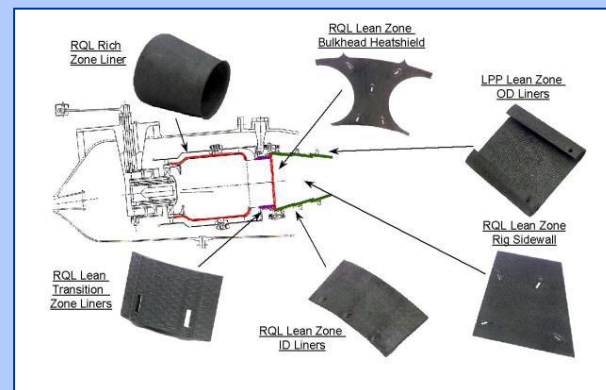
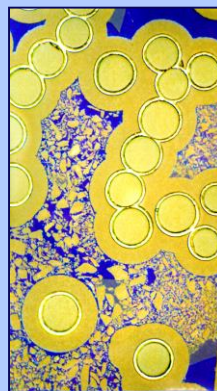
# NASA Glenn— Fiber / CMC / EBC R&D, Leadership, and Teaming

- We have been leaders in the assessment and development of **SiC fibers**, **SiC/SiC CMCs**, and **EBCs** for application in advanced, efficient gas turbine engines for decades.
- We have collaborated with Industry, Academia, and DOD (Department of Defense) Labs for over 25 years.



# NASA Glenn—MI and CVI\* SiC/SiC Development

- **Early 1990s:** The **NASA Enabling Propulsion Materials (EPM) Program** allowed NASA to work closely with Industry to tackle a **broad range of CMC technologies (including EBCs)** required to reduce NO<sub>x</sub> emissions and airport noise through advancements in enabling materials (Refr. 5, 6).

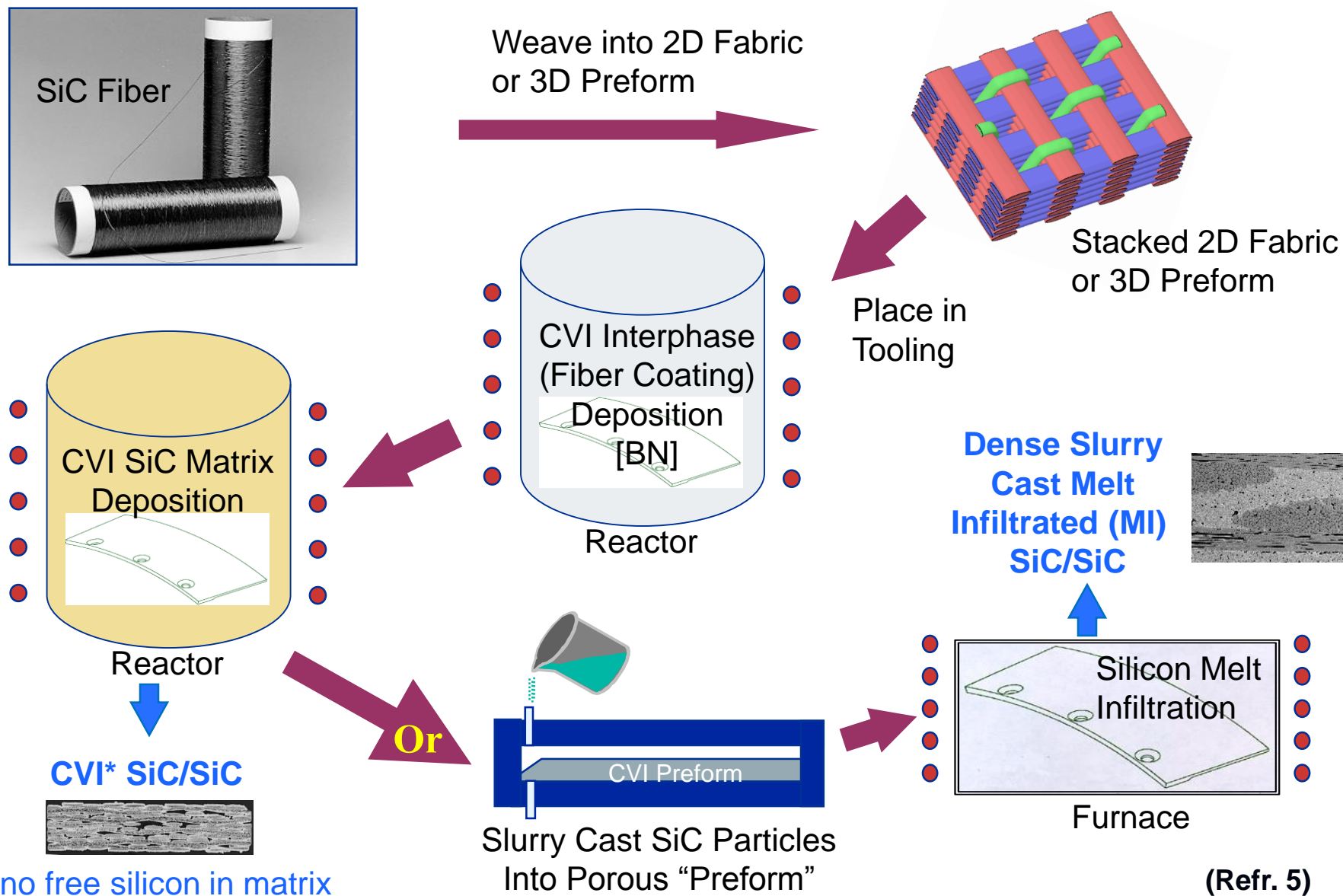


## Development of MI (Melt Infiltrated) SiC/SiC for Combustor Liner Application

\* CVI— Chemical Vapor Infiltration



# CVI and MI SiC/SiC CMC Manufacturing Processes



# Example of the Microstructure of a 2D SiC/SiC CMC\*

**As-Fabricated Slurry Cast Melt Infiltrated (MI) SiC/SiC Material**  
*Polished Section—Examined With FESEM*

90° SiC Fiber Tow

MI SiC Matrix

A

0° SiC Fiber Tow

\* Fabricated by GE Power Systems Composites

Q-126 6.0kV 11.9mm x250 SE(L) 7/6/2015

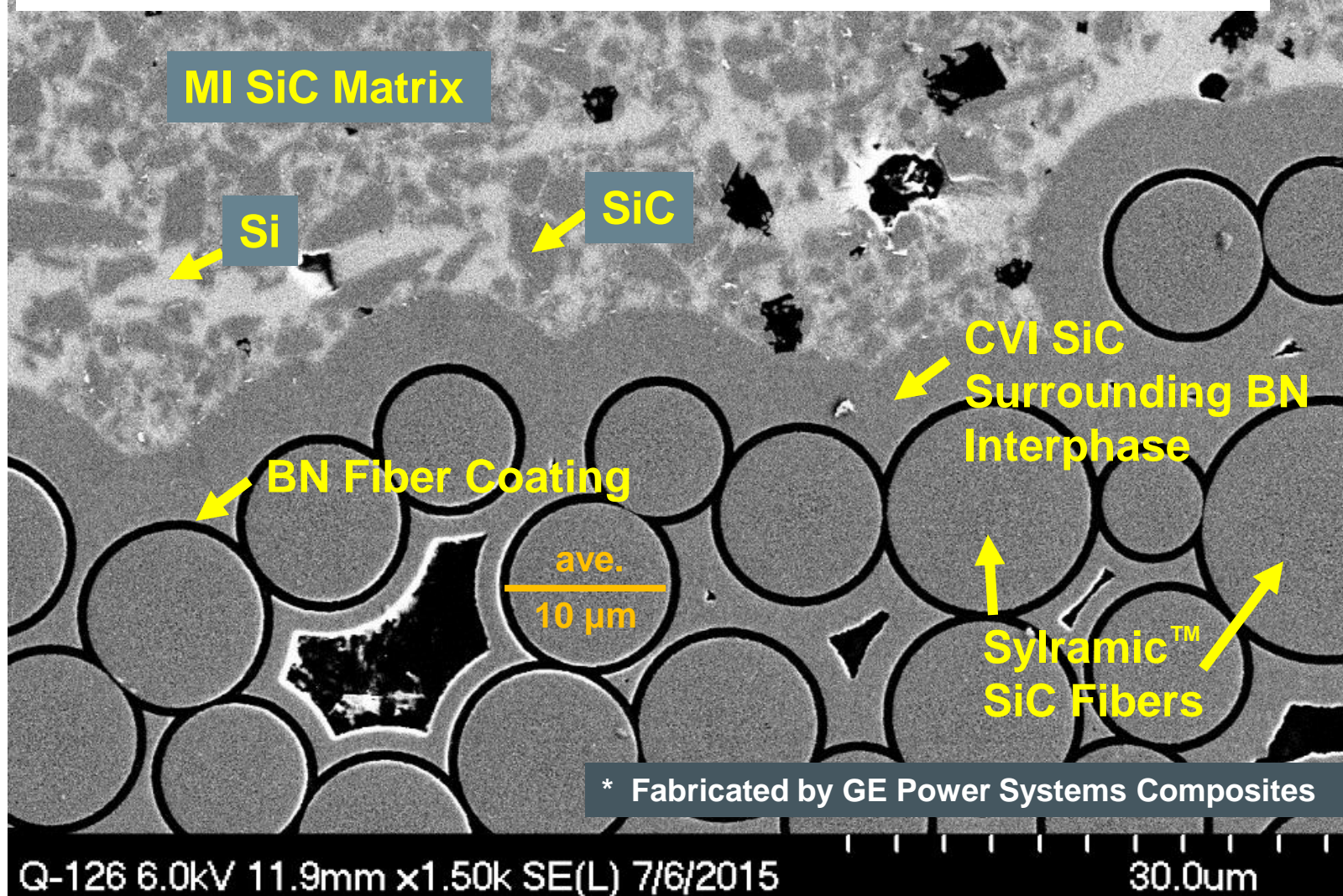
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# Example of the Microstructure of a 2D SiC/SiC CMC\*

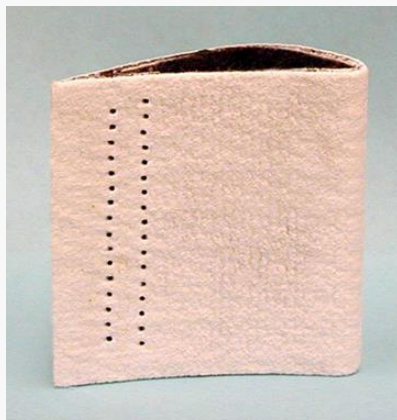
**As-Fabricated Slurry Cast Melt Infiltrated (MI) SiC/SiC Material**  
*Polished Section—Examined With FESEM*

**A**



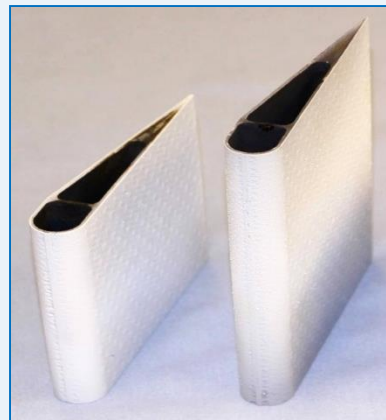
## NASA Glenn—SiC/SiC and EBC Development

- The **NASA Ultra-Efficient Engine Technology (UEET) Program** continued the advancement of Melt Infiltrated (MI) SiC/SiC CMC and EBC technology for commercial aircraft engines (Refr. 7 - 10).



MI CMC Vane w/EBC:  
NASA UEET Program

Refr. 7, 8



CVI SiC/SiC Vane  
Test Articles w/EBC:  
NASA ERA Project

Refr. 11

- GRC has further developed “High Temperature” SiC/SiC (*no free silicon in matrix*) and EBCs for use above 2600°F (1427°C) in subsequent NASA Programs/Projects including:
  - **Next Generation Launch Technology (NGLT) Project** - **Hypersonics Project**
  - **Supersonics Project** - **Aeronautical Sciences (AS) Project**
  - **Environmentally Responsible Aviation (ERA) Project**
  - **Transformational Tools and Technology (TTT) Project**



# SiC/SiC Components for Gas Turbine Engines: Benefits

- Reduced component weight (1/3 density of superalloys)
- Higher temperature capability/increased thermal margin
- Reduced cooling requirements
- **Improved fuel efficiency** → **further increase with 2700°F CMC components**
- Reduced emissions ( $\text{NO}_x$  and CO)



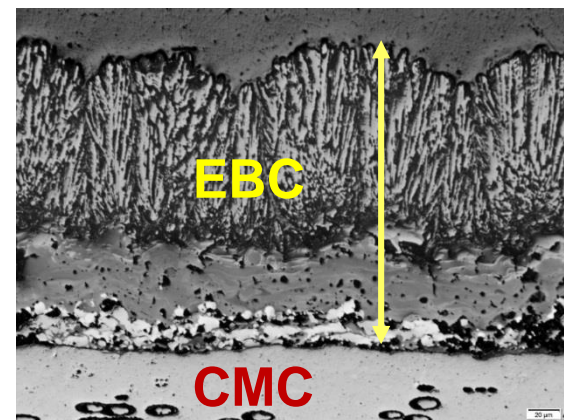
**Incentive to Increase Engine Operating Temperatures**

## Current / Future CMC/EBC System Research at NASA GRC

- **2700°F SiC/SiC Development & Characterization**
- **Durable, High Temperature (3000°F) EBC**
- **High Temperature (2700°F Capable) SiC Fiber**
- **SiC/SiC CMC / EBC Durability Modeling & Validation**

### Goal:

- Overall, ICME (Integrated Computational Materials Engineering) Culture
- All CMC/EBC Research Involving / Influenced by Modeling

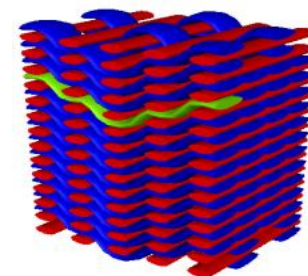


Refr. 12

# Hybrid (CVI + PIP) SiC/SiC CMC Manufacturing Process

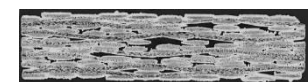
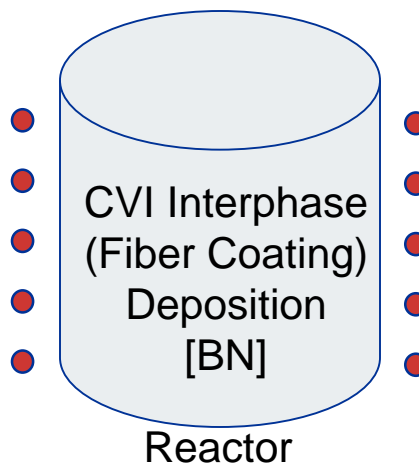
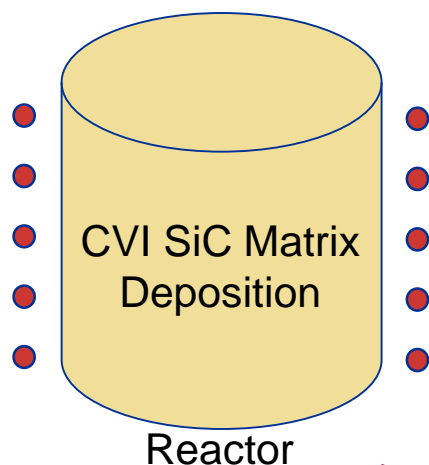


Weave into 2D Fabric  
or **Designed** 3D Preform

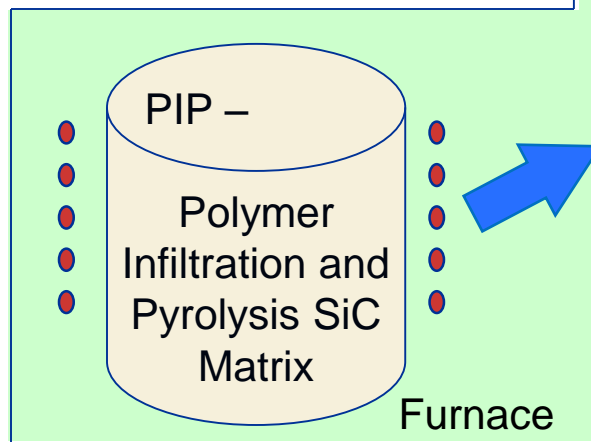


Stacked 2D Fabric  
or 3D Preform

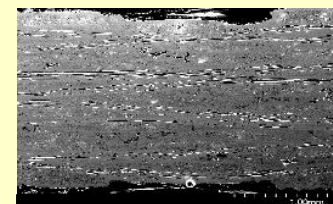
Place in  
Tooling



Porous "Preform"



**Dense Hybrid SiC/SiC  
For 2700°F Application**



**no free silicon in matrix**

Refr. 12

# High Temperature CMC Testing: Tensile Creep and Fatigue

**Testing used to validate models  
for CMC and CMC / EBC samples**

## Instron Test Rig

- Testing in Air
- Temperatures up to 2800°F (1538°C)
- Creep and Fatigue
- Frequencies up to 1 Hz
- Electromechanical, 50 kN Load Cell
- MoSi<sub>2</sub> Element Furnace
- 1 in. Gage Length, Water-Cooled Extensometer

**Typically Test 6 in. Long  
Tensile Specimens**



**Example of Rig Used to Test SiC/SiC CMCs**



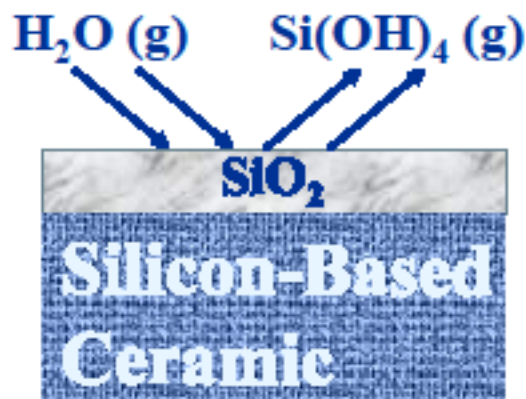
## Importance of Environmental Barrier Coating (EBC)

- Reaction with water vapor from combustion environment causes rapid surface recession of Si-based ceramics, seriously limiting component life



- An Environmental Barrier Coating (EBC) provides protection from water vapor and enables long life.

Volatilization → Surface Recession



Durable System

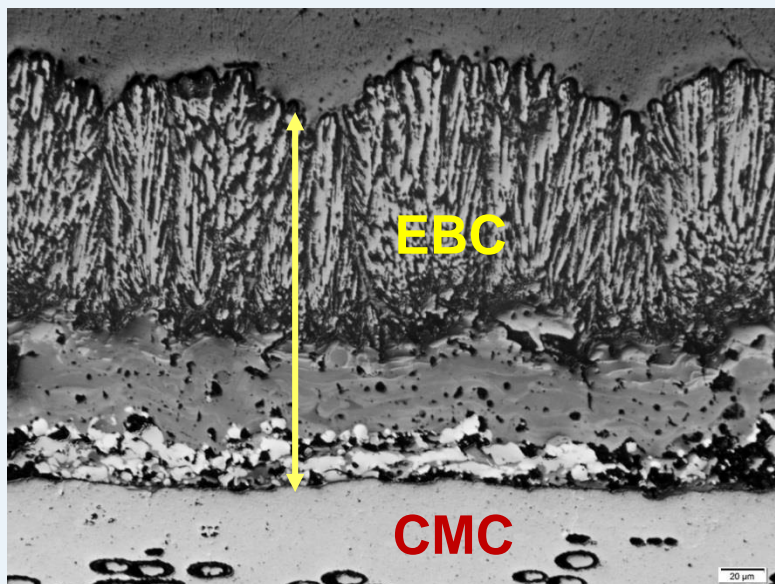


# Durable, High Temperature EBC for Use With 2700°F SiC/SiC

- Issue:**
- Need for EBC systems with **up to 3000°F (1650°C) capability** that exhibit **low thermal conductivity** and **high temperature durability**.
  - EBC design (thickness/composition/etc.) is **component dependent**.

**Addressed By:** EBC (environmental barrier coating) systems designed with:

- High melting point / oxidation resistant systems capable of up to 3000°F
- Advanced environmental barrier and 2700°F+ capable bond coats
- Controlled surface emittance and radiative properties
- High strength and self-healing capabilities, CMAS-resistant
- Low thermal conductivity 0.5-1.2 W/m-K at 2700-3000°F (1482-1650°C)



## Multilayer / Multifunctional EBC

Multicomponent low conductivity, high stability Rare Earth (RE) doped  $\text{HfO}_2$ ,  $\text{ZrO}_2$  and Hf (Zr)-RE silicates

Strain tolerant oxide-silicate interlayers

Rare Earth-Silicate and  $\text{HfO}_2$ -Rare Earth-Alumino-Silicate EBC

$\text{HfO}_2$ -Si or RE-Si based bond coats

SiC/SiC Composite

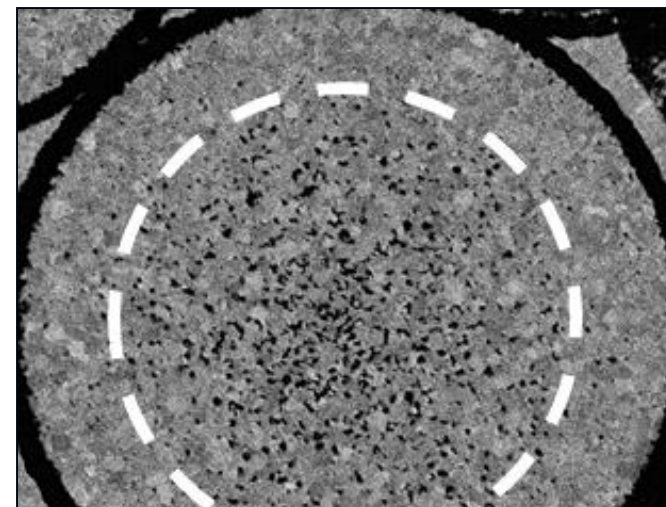
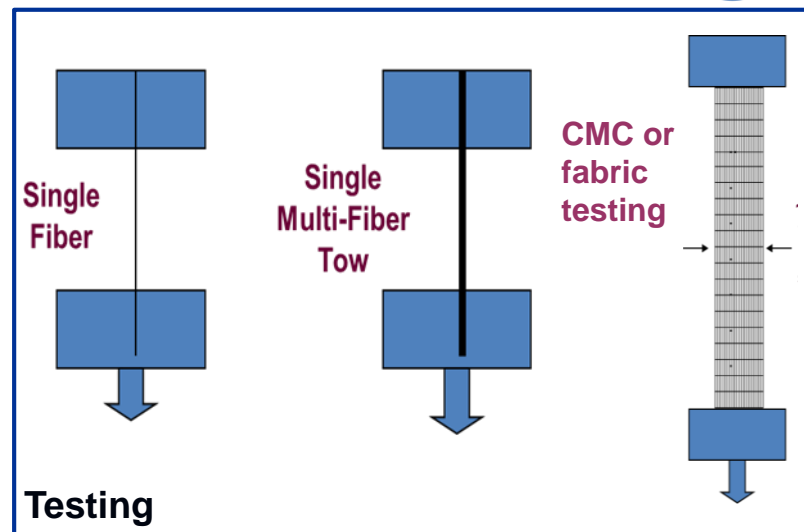
Refr. 10

# High Temperature (2700°F (1482°C)) SiC Fiber Research

**Issue:** SiC/SiC CMCs that will operate at 2700°F will require **strong, creep-resistant SiC fibers**.

**Addressed By:**

- Determination of key mechanical/structural properties of potential 2700°F SiC fibers to:
  - Understand basic mechanisms and **correlation** with microstructure
  - Develop analytical fiber and CMC models for time-temperature deformation and rupture behavior
  - Identify current limitations and approaches for property improvement
- GRC fiber processing: obtain 2700°F SiC fiber with improved microstructure (reduced porosity, specific SiC grain size, etc.) and optimal properties



Example of Increased Amount of Porosity in SiC Fiber Core

# GRC Modeling of CMC/EBC Behavior/Properties/Durability

- **Modeling:** We have a broad perspective and work with everyone

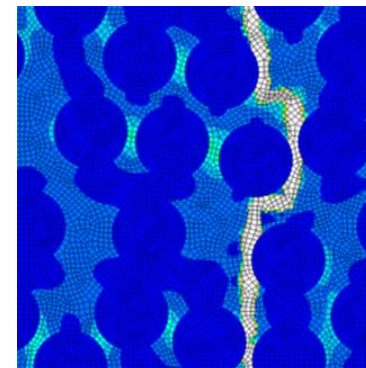
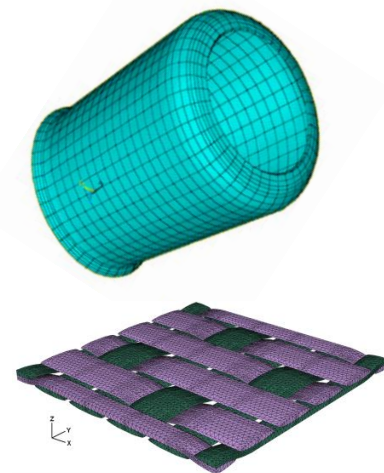
**Issue:** Need for a wide range of approaches (different scales) for CMC and CMC/EBC system modeling to provide understanding of behavior / performance;  
- **enabling life prediction** and **guiding of CMC and EBC durability enhancement**.

## **Addressed By:**

- Large portfolio of internal codes/software
- **Multiscale modeling**
- Computationally-efficient methods/tools
- Account for environmental effect: Air, vacuum, inert, steam, CMAS
- Creep/fatigue interaction with environment
- Unique/creative non-linear modeling capabilities
- Proposed use of a model SiC/SiC material system and mini-composites in some studies
- *Strong collaboration with industry*



- Validation of models (CMC and CMC/EBC system)
- Understand the effects of the constituents/structure







## **Summary**

- **NASA's efforts have helped move SiC/SiC CMC and EBC technology forward to the point where CMC components are being introduced in commercial jet engines.**
- **Aircraft gas turbine engines will continue to operate at *higher temperatures*, and there will be a need for higher-temperature (>2500°F/1371°C) SiC/SiC composites and EBCs.**
- **A 2700°F capable fiber is an enabling constituent for a durable 2700°F CMC/EBC system.**
- **Analytical modeling of material behavior is needed to help understand CMC/EBC durability issues, and to provide guidance for material development.**



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## **Appendix—Back-up Slides**



# Investigation of CMAS Interactions with EBC Materials

- **CMAS: Calcium magnesium aluminosilicate**

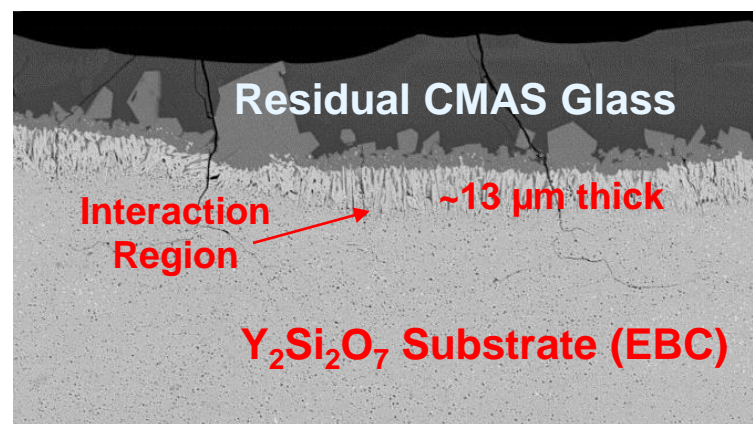
**Issue:** Ingested particulates (e.g., sand) can form CMAS glass deposits on EBCs in the engine hot section, with coating degradation occurring due to reaction and infiltration of the coating.

**Addressed By:**

- Characterization of thermal and mechanical properties of CMAS glass provides fundamental knowledge that will help to mitigate damage and improve EBC durability
- Evaluation of interactions between heat treated EBC substrates with CMAS glass pellets. EBC materials evaluated include:
  - Yttrium disilicate ( $\text{Y}_2\text{Si}_2\text{O}_7$ )
  - Hafnium silicate ( $\text{HfSiO}_4$ )
  - Ytterbium disilicate ( $\text{Yb}_2\text{Si}_2\text{O}_7$ )



Aircraft Engines Ingesting Sand on Runway



$\text{Y}_2\text{Si}_2\text{O}_7$  Substrate Exposed to CMAS at 1200°C for 20h





NASA Headquarters



Ames Research Center



Armstrong Flight Research Center



Glenn Research Center



Goddard Space Flight Center



Jet Propulsion Laboratory



Johnson Space Center



Kennedy Space Center



Langley Research Center



Marshall Space Flight Center



Michoud Assembly Facility



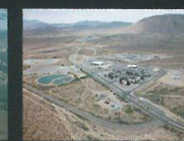
Plum Brook Station



Stennis Space Center



Wallops Flight Facility



White Sands Test Facility

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